Design of a new quasi-axisymmetric stellarator

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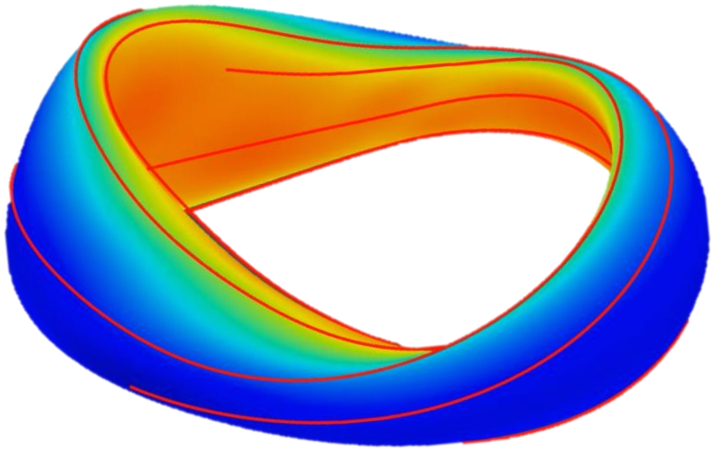
Acknowledgement to:
Y. Turkin, J. Nührenberg, J. Geiger, E. Strumberger, M. Borchardt

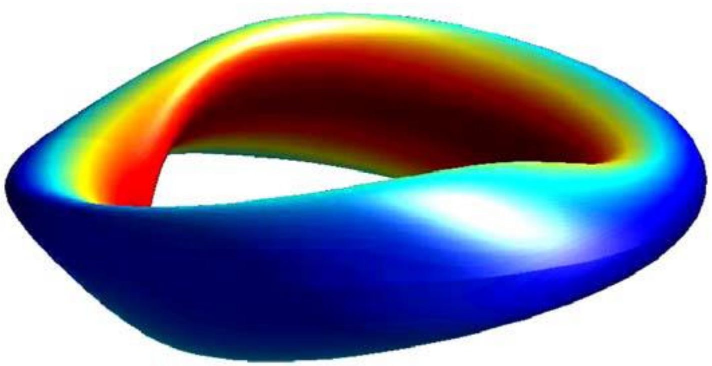
Overview of this talk

- Quasi-axisymmetry and quasi-axisymmetric stellarator designs
- ROSE: the optimization code used
- The new configuration: QuASDEX
  - Loss-fraction rates of fast particles
  - Stability properties
  - Neoclassical properties
  - Preliminary coils
- Summary and future work



Quasi-axisymmetry (QA)

- **What is quasi-axisymmetry?**
  - The magnetic field strength is nearly independent of the toroidal Boozer coordinate: $\mathrm{B} \approx B(s, \theta)$ with $s = \frac{\psi}{\psi_a} \approx \frac{r^2}{a^2}$. This reduces the radial drift of trapped particles.
  - Because of the toroidal symmetry of the magnetic field strength, QA-configurations share many neoclassical properties of tokamaks, such as high bootstrap current.

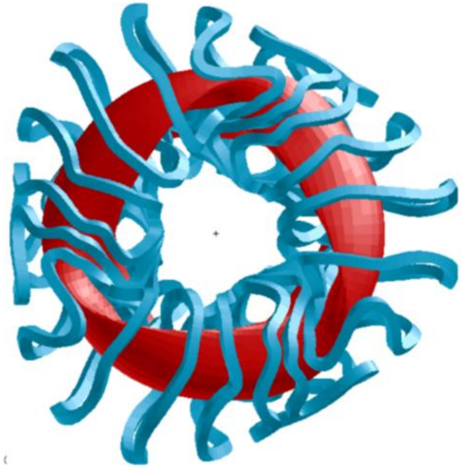


ESTELL: [1] M. Drevlak et al. Contrib. Plasma Phys., 53, (2013)

- **What are potential benefits of a quasi-axisymmetric compared to other stellarators?**
  - Reduced neoclassical transport
  - Compact: High bootstrap current fraction could potentially simplify coil design and allow for a more compact device.

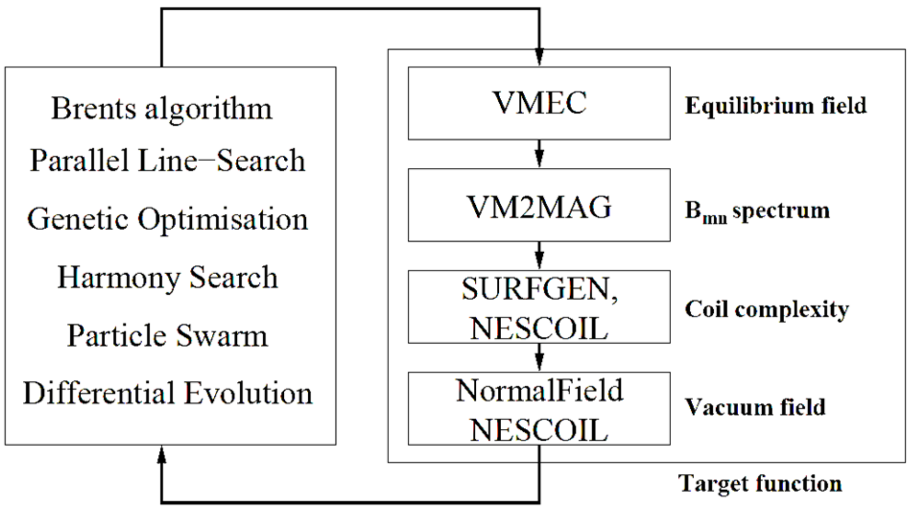
Previous designs & goal of this study

- First quasi-axisymmetric equilibrium was presented in 1994 by Nührenberg, Lotz and Gori (Theory of Fusion Plasmas Varenna, page 3, (1994))
- Several others have followed, e.g.
  - CHS-qa (Okamura et al., Nuclear Fusion (2001))
  - ESTELL (Drevlak et al. Contribu. Plasma Phys., (2013))
  - NCSX (Neilson et al., Fusion Engineering and Design, (2003); Neilson et al., IAEA-CN-94/IC1)
    - R/a=4.4, R=1.4m, N=3, B=1.2-1.7T, Rotational transform=0.39…0.65, $\beta < 4\%$



- Can one find configurations which improve on these previous studies?:
  - Compact design (aspect ratio R/a of 3 to 4)
  - MHD stable
  - Small fast-particle loss rates to provide fusion-relevant knowledge

ROSE ("ROSE Optimises Stellarator Equilibria")

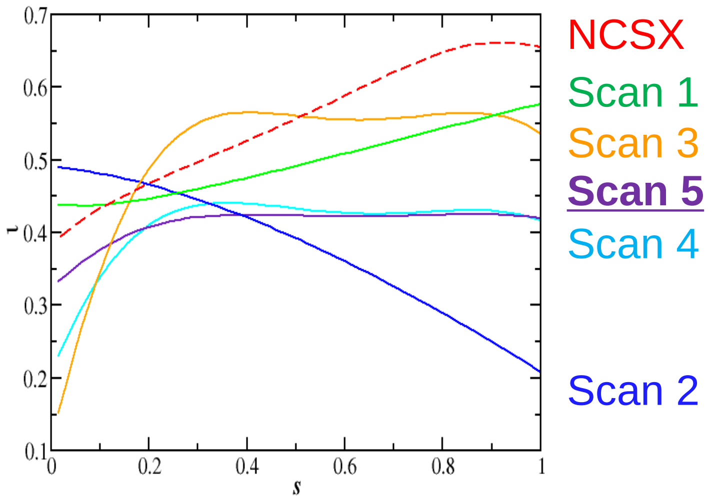


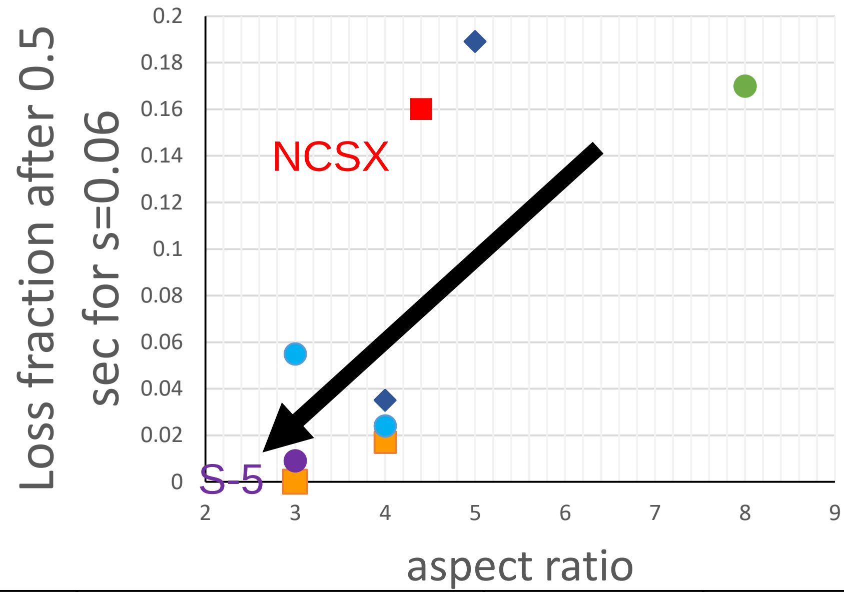
- Targeted criteria in this study (ROSE can handle many more):

- Rotational transform at the axis and the plasma boundary
- Average of the absolute Gaussian curvature on the plasma boundary
- Maximum of the absolute values of the two principal curvatures of the plasma edge
- Vacuum magnetic well $\frac{\partial}{\partial \psi} \int \frac{dl}{B} < 0$
- Vacuum rotational transform
- Quasi-axisymmetry by reducing $\sum_{n \neq 0, m}^{\infty} B_{n,m}^2 / B_{00}$

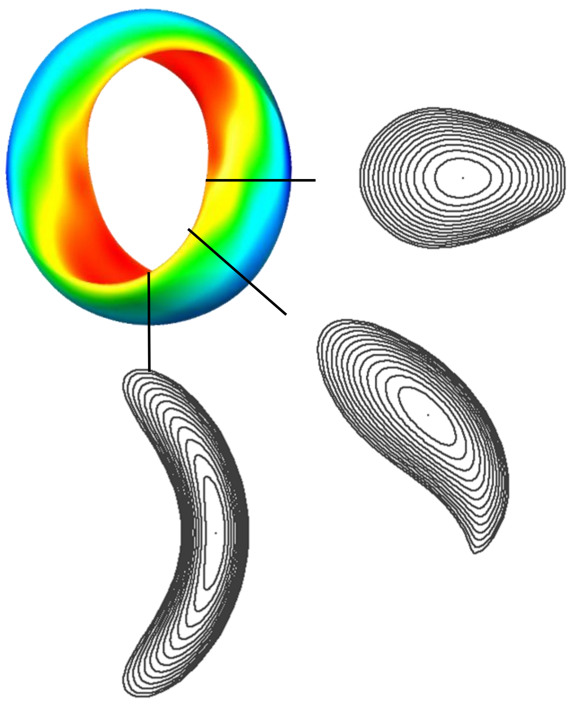
Drevlak et al., paper in preparation

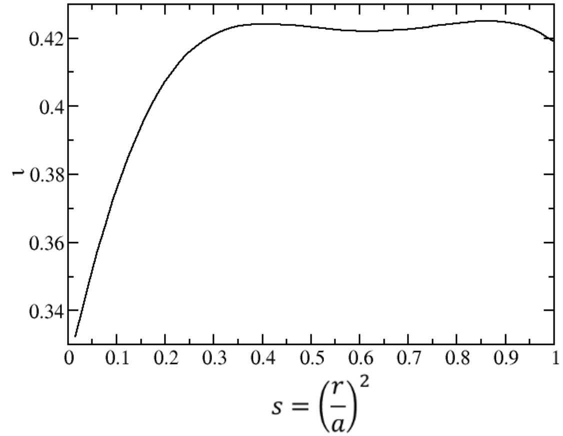
Overview of results





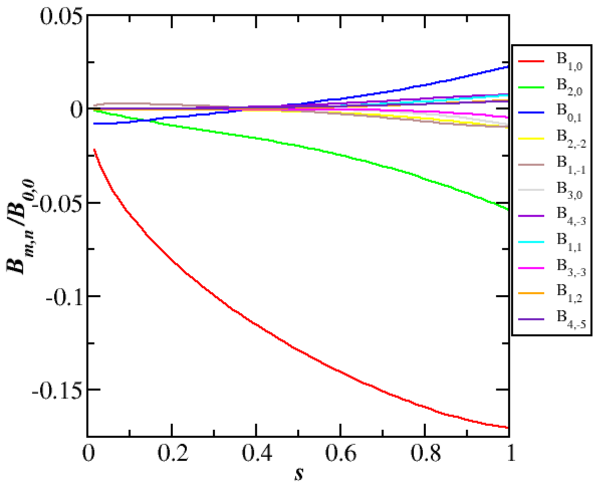
	Scan 1	Scan 2	Scan 3	Scan 4	Scan 5/S-5
current and beta	Without plasma current or beta	Plasma current peaked on axis; beta ~ 3%	Bootstrap-like current profile; beta ~ 3%	unchanged	unchanged
iota axis	0.4	0.46	0.15	0.2	>0.3
iota edge	0.6	0.2	0.55	0.45	<0.5
external iota	-	0.2	0.15	0.25	>0.3
Aspect ratio	3,4,5,**8**	3,**4**,**5**	**3**,**4**	**3**,**4**	3,4
NFP	2,**3**,4,5,6	1,**2**,3	1,**2**	**2**,3	2
MHD stable	-	-	unstable	unstable	stable

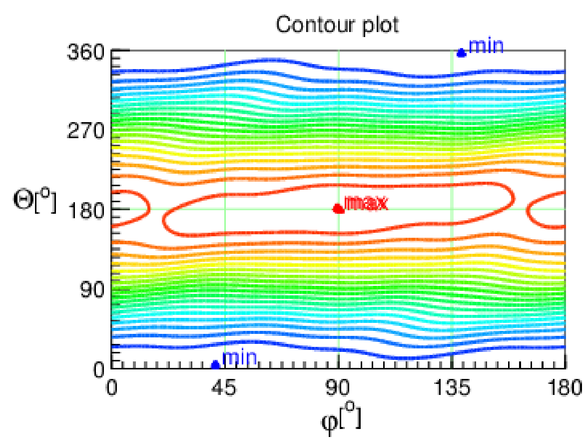


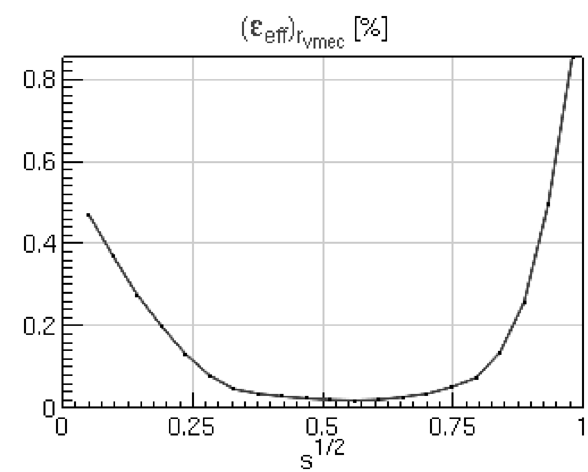


Aspect ratio	3.4
Beta	3.5%
Vacuum iota	0.32
Effective ripple at s=0.3	0.013%

- The non-quasi-axisymmetric components of the magnetic field strength are below 2.5% of the B_{00} mode on axis.
- The magnetic field strength contours appear quasi-axisymmetric



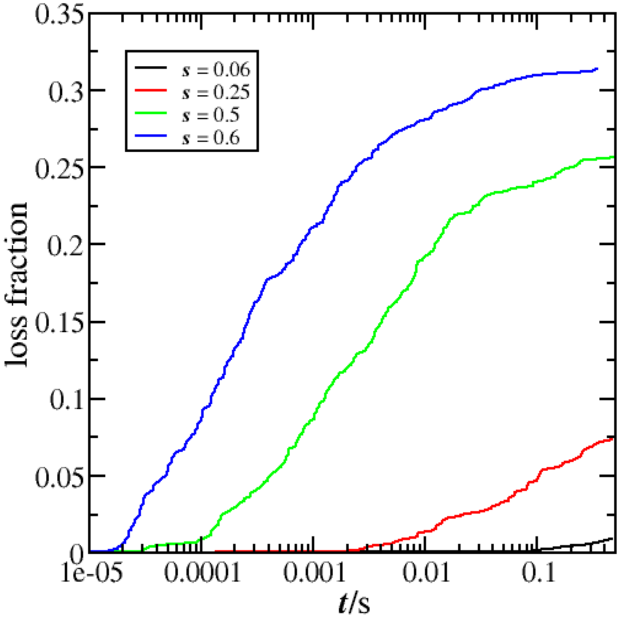




Fast particle losses (with ANTS*)

ANTS: plasm**A** simulatio**N** with drif**T** and collision**S**

- The volume is scaled to reactor size: **1900m³** with a major radius of **10.3m** and a minor radius of **3.1m**.
- Volume-averaged B=5T for the loss fraction calculation.
- The total toroidal current is 2.5MA (with roughly bootstrap profile; for the reactor-sized configuration).
- Guiding center drifts calculated without collisions
- For the flux surface $s = 0.06$ the loss fraction in 0.5 seconds is below 1%
- For the flux surface $s = 0.25$ (which corresponds to a normalized radius of 0.5) the loss fraction of fast particles is 7.4%.



M. Drevlak, J. Geiger, P. Helander and Y. Turkin, Nucl. Fusion, 54, (2014)

$$s = \left(\frac{r}{a}\right)^2$$

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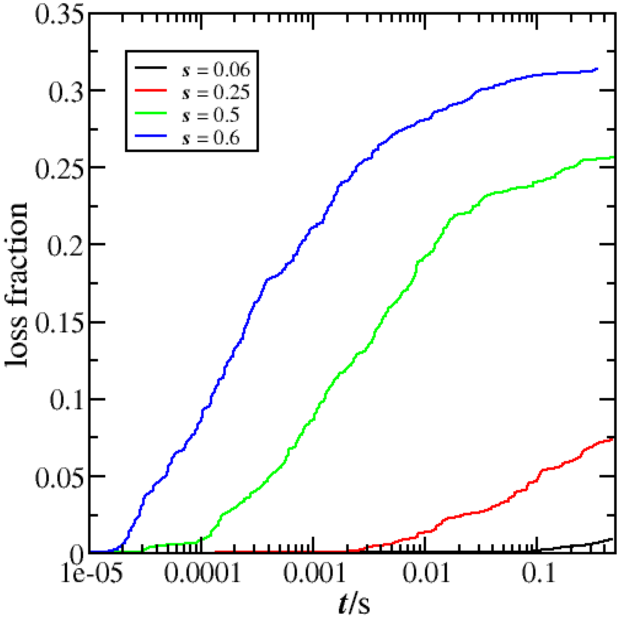

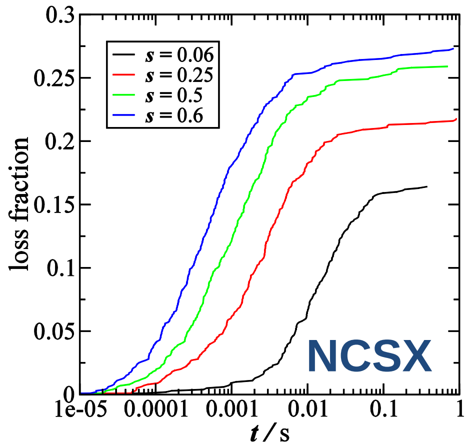

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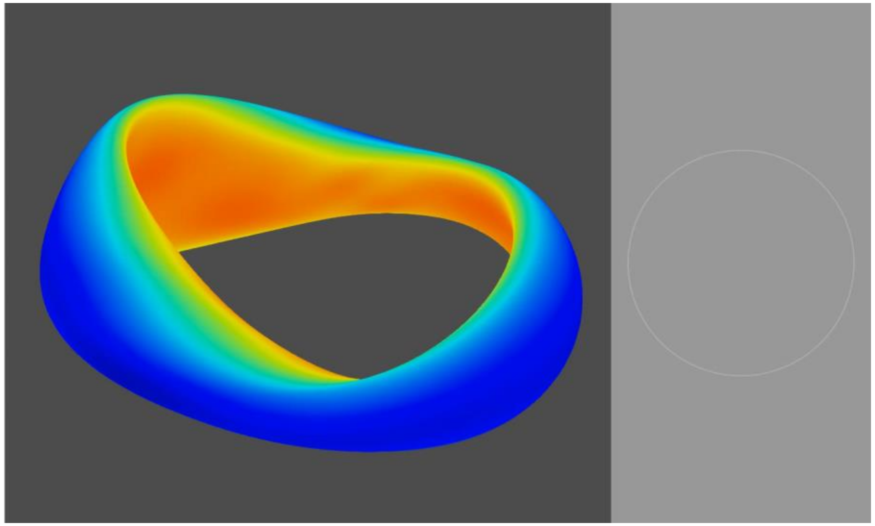
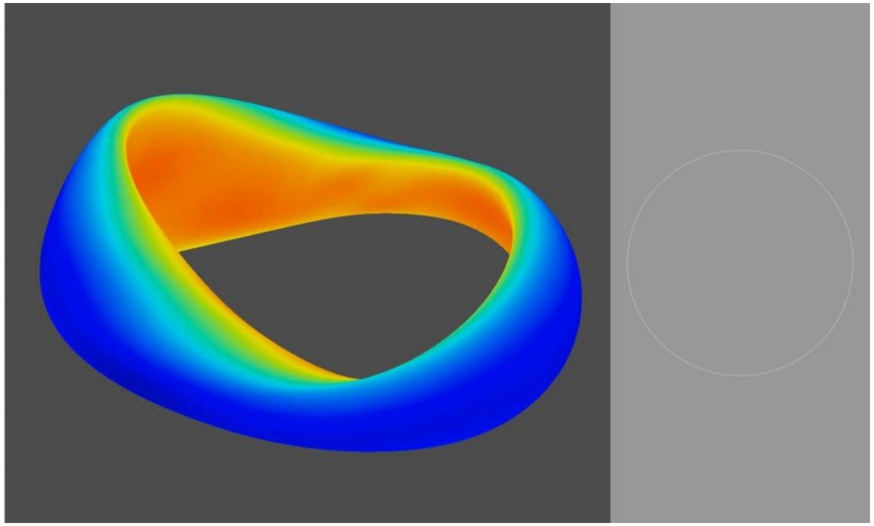
M. Drevlak, J. Geiger, P. Helander and Y. Turkin, Nucl. Fusion, 54, (2014)

paths of particles

- Passing particle
- Trapped particle

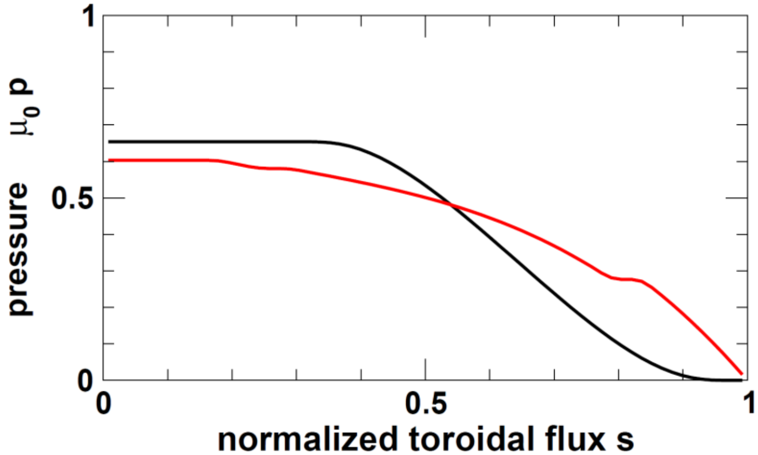


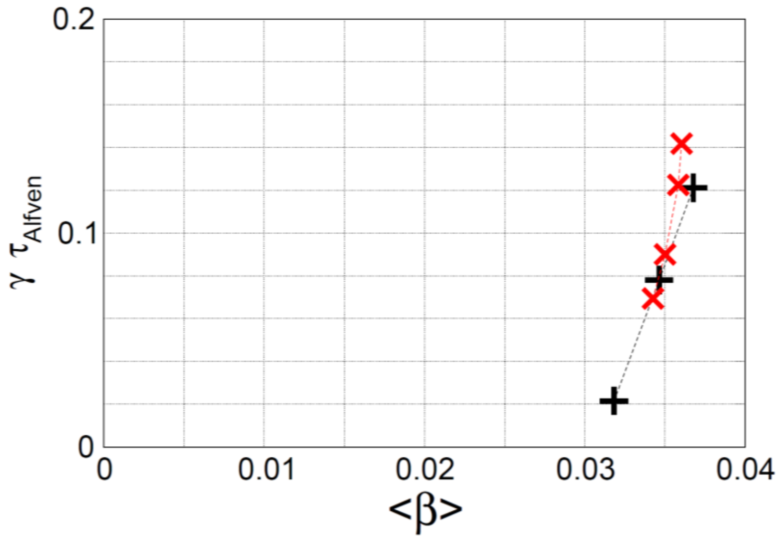


Stability

by Carolin Nührenberg

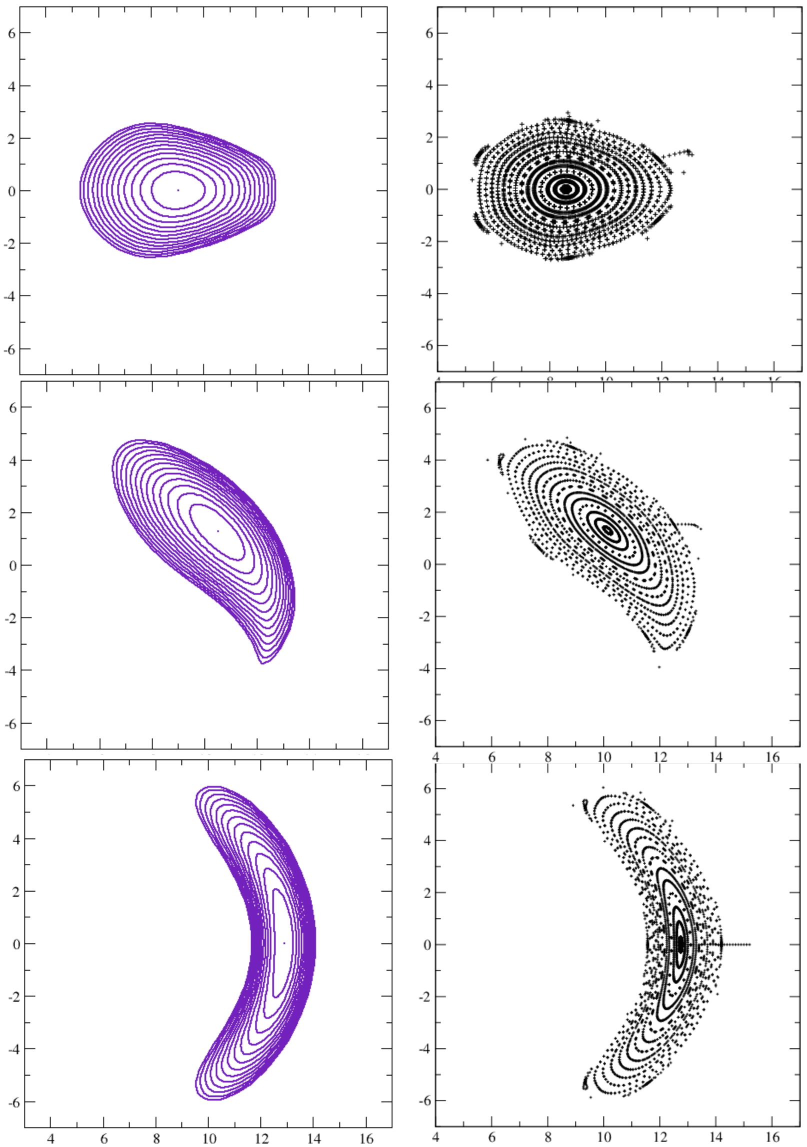
- The stability was evaluated with CAS3D*.
- The pressure profile was altered to test the effects on stability.
- A stability beta limit of 3% was found.



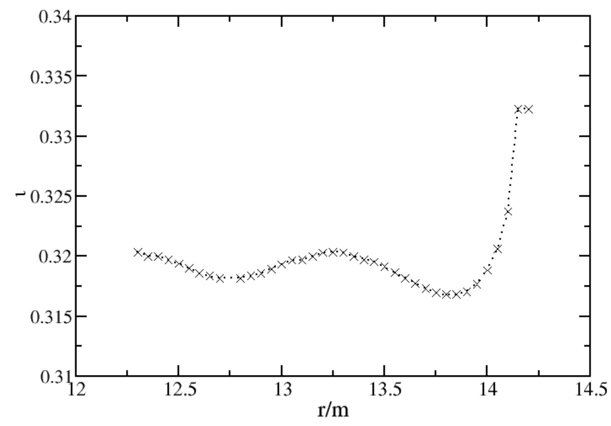


*C. Schwab, Phys. Fluids 5 (1993) 3195

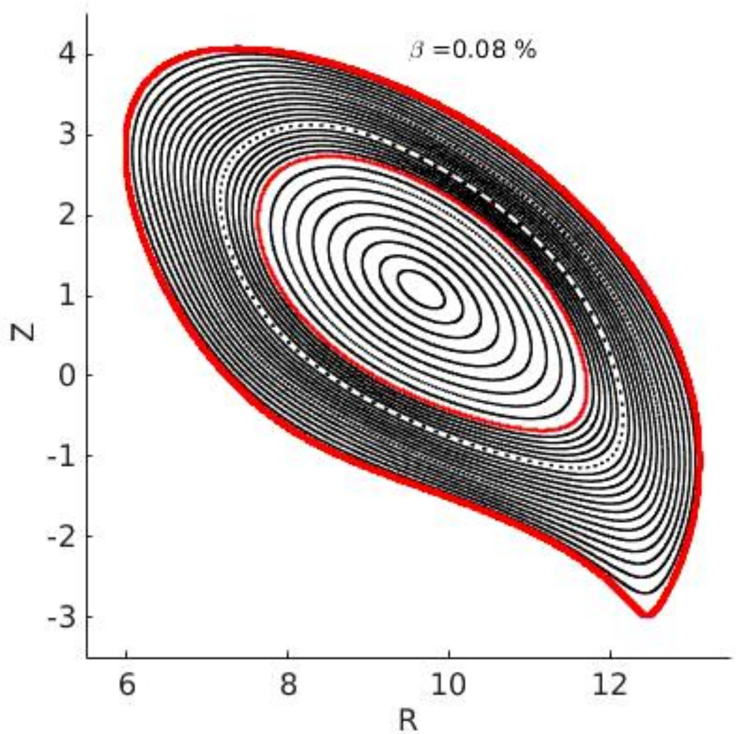
Vacuum properties of new configuration



- In vacuum, well defined flux surfaces can be seen with no islands inside the plasma
- However this is not the final vacuum field, since it is not generated with coils



- Beta scan without current**



by Joaquim Loizu

*S. R. Hudson et al, Phys Plasmas 19 (11), 112502 (2012), J. Loizu et al, Phys Plasmas 23 (11), 112505 (2016)
**J. Loizu et al, J Plasma Phys 83, 715830601 (2017)

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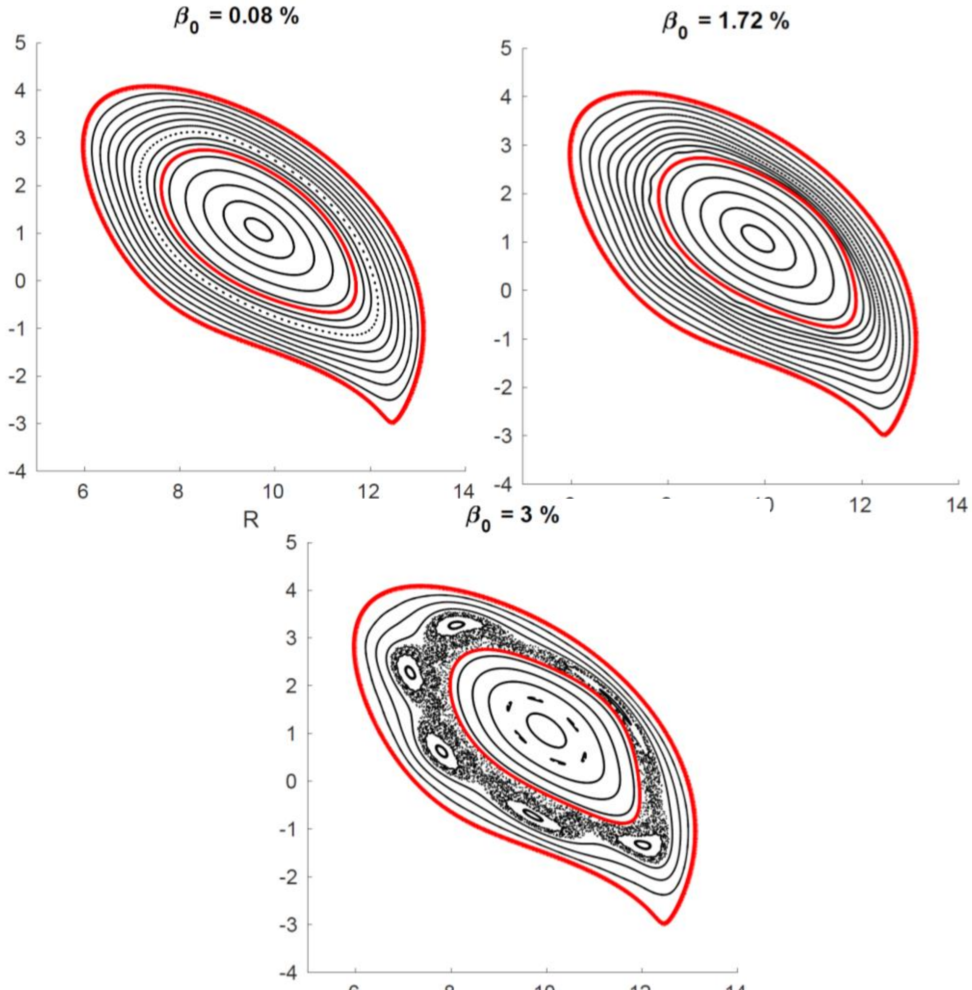

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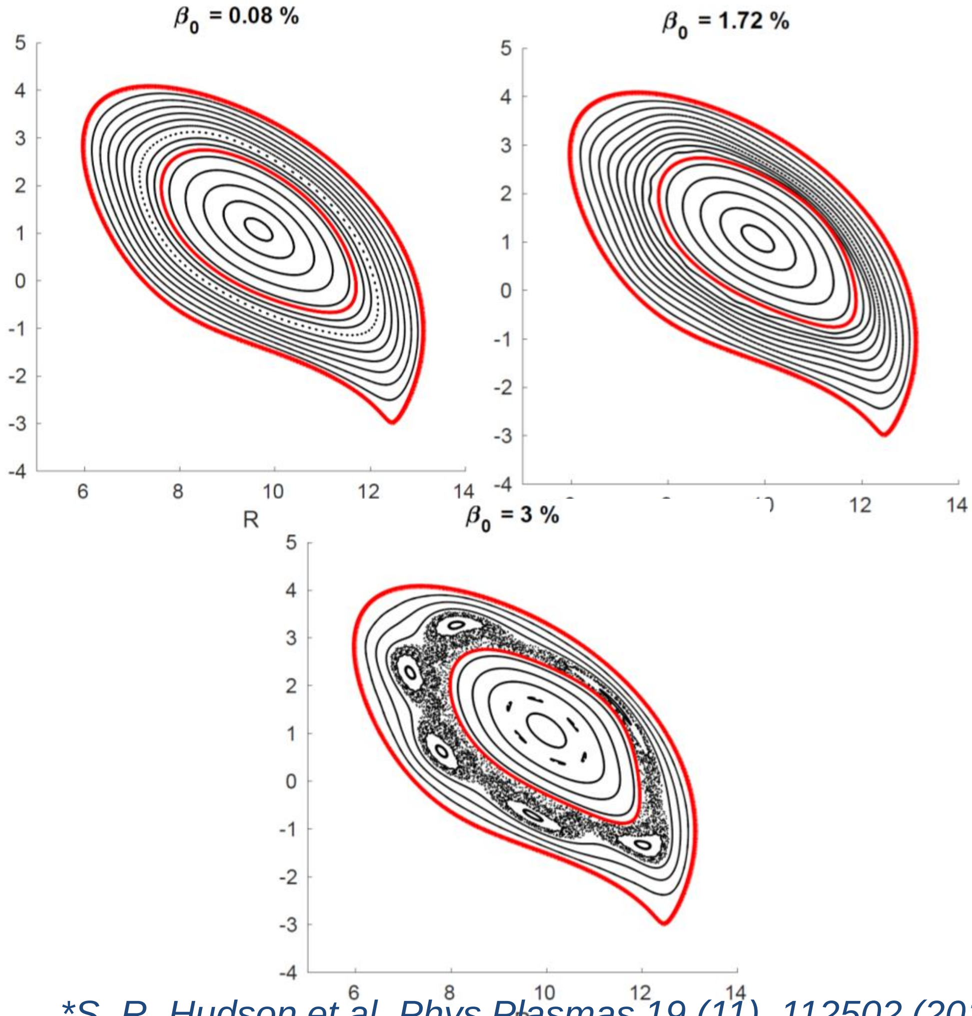
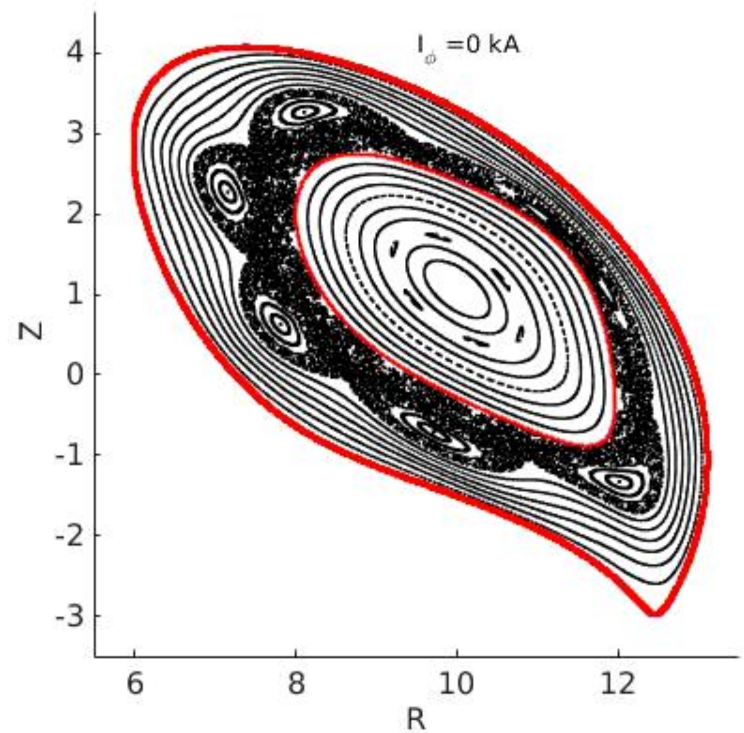


- Current scan with beta=3%**



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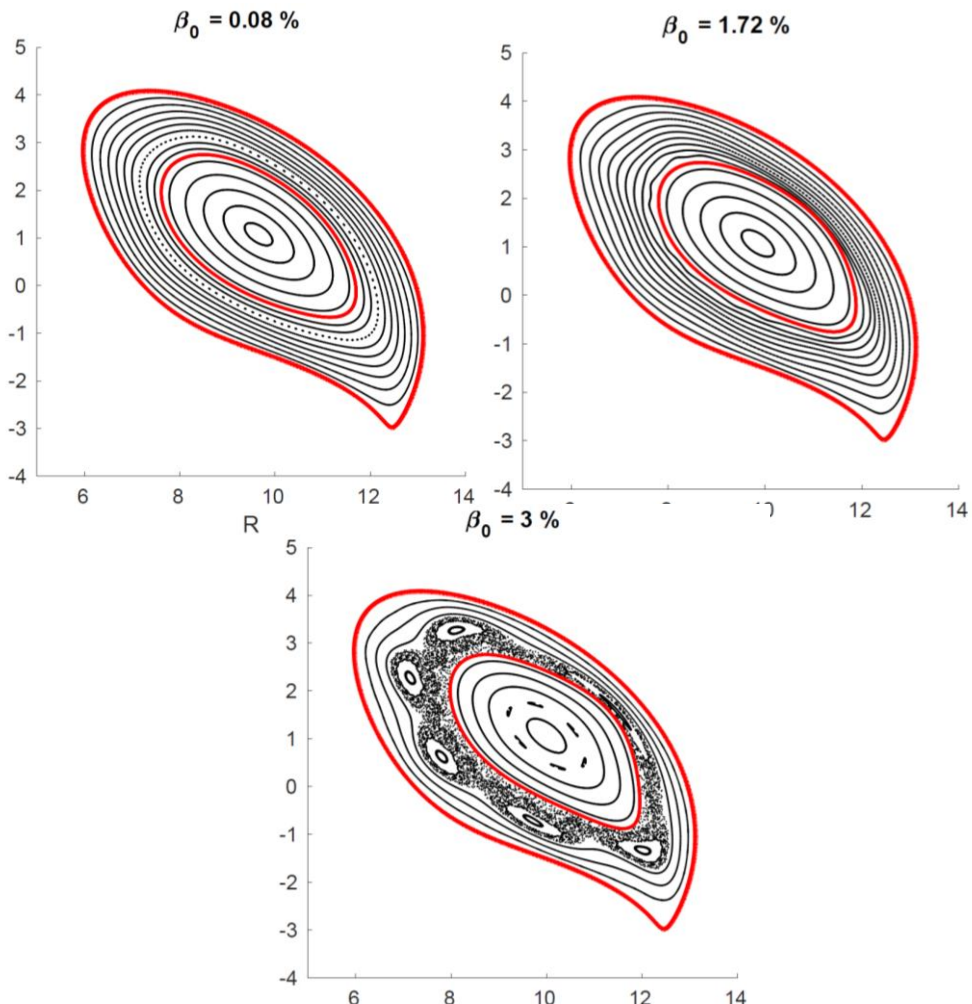

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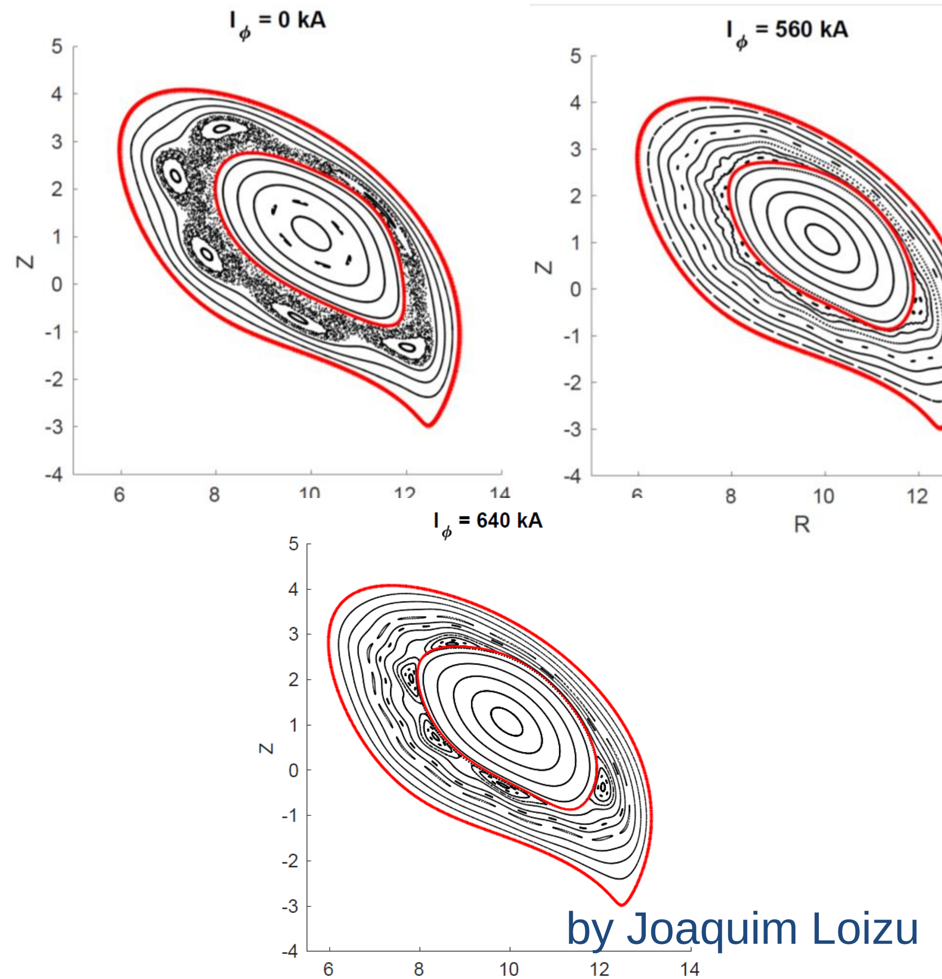

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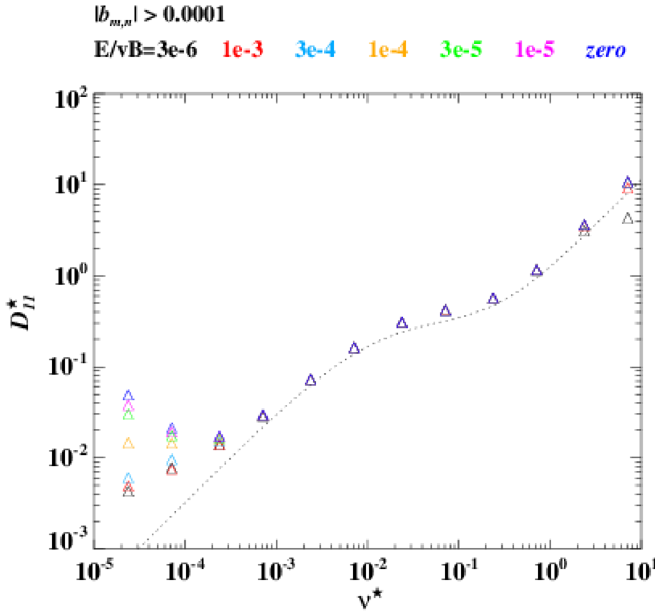
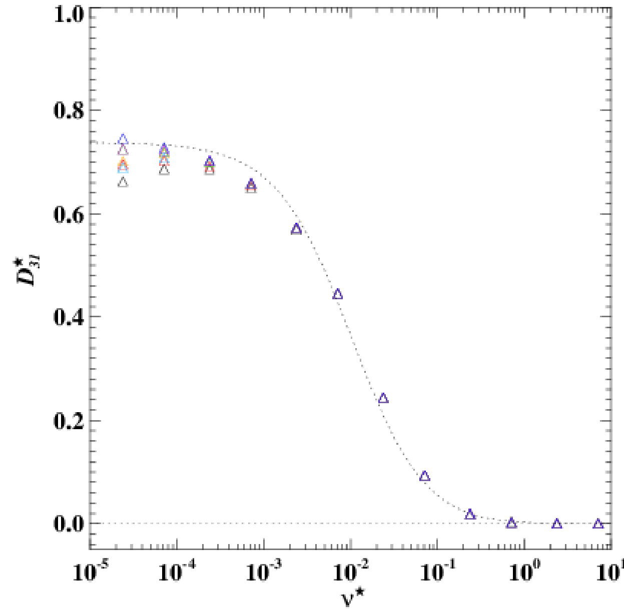
Radial transport:



Bootstrap current:



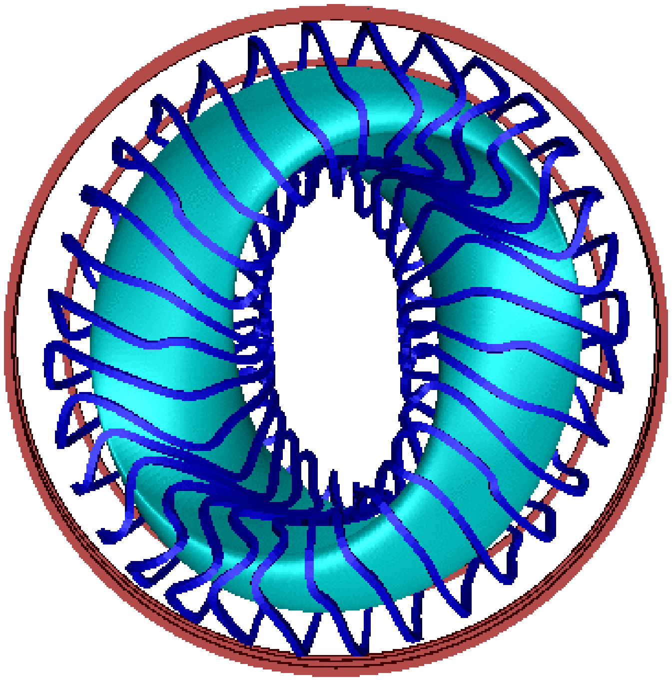
- The mono-energetic transport coefficients have been evaluated with DKES*.
- Transport coefficients are very similar to those in an equivalent tokamak at r=0.5

*S. Hirshman, *et al*., Phys. Fluids **29** (1986) 2951

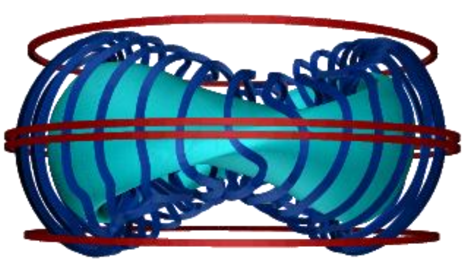
Preliminary coils (reactor size)

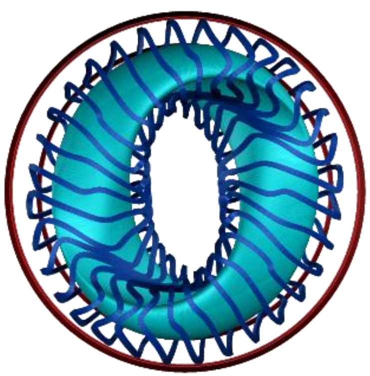
by Michael Drevlak

With ONSET



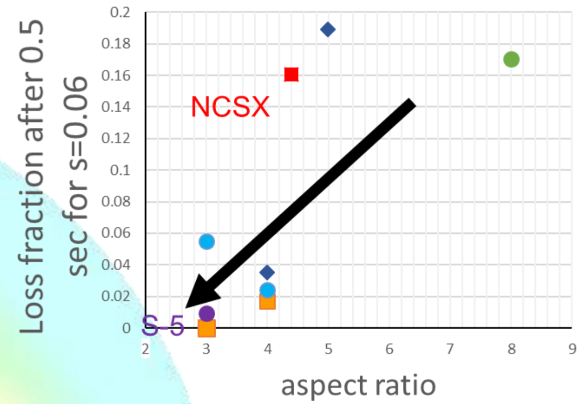
- 8 types of modular coils → 32 modular coils with additional 4 poloidal field coils
- Smallest radius of curvature appears near the quarter period poloidal cross section, due to the strong plasma edge shaping (~63cm)
- Maximum relative magnetic field error of around 4.1%
- Mean relative magnetic field error of 0.95%
- Clearance of coil to coil > 51cm everywhere





Summary

- A study of quasi-axisymmetric stellarator equilibria with different iota profiles, aspect ratios, and number of field periods has been performed
- A compact (A=3.4), MHD-stable, two-field period stellarator has been found with small fast-particle loss fractions.



Future work:

- Keep searching for even more improved configuration, e.g. relaxing the magnetic well constraint by using MHD stability directly.
- Optimizing with consistent bootstrap current (depends on the collisionality).
- Optimizing coils further
- Developing divertor concept